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Predicting the onset of cracks in bulk metal forming by ductile damage criteria

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Abstract

Three different ductile damage criteria, Ayada, normalized Cockcroft and Latham and a new shear stress based criterion taking into account hydrostatic tension, are utilized for predicting the onset of cracks in various deformation processes. It is found that the Ayada criterion predicts well the onset of cracks when they originate from hydrostatic tension. The shear based criterion predicts cracks triggered by shear and the normalized Cockcroft and Latham criterion indicates the overall area of onset of cracks caused by either hydrostatic or shear stresses. However the prediction is not as accurate as the Ayada criterion for cracks caused by hydrostatic tension.

Peer-review under responsibility of the scientific committee of the International Conference on the Technology of Plasticity.

Keywords: Metal forming; ductile damage; crack initiation

1. Introduction

The ability to predict the occurrence of cracks in metal components during bulk forming has been a research topic for many years. Examples of such cracks are arrowhead (chevron) cracks occurring in forward rod extrusion or drawing, and surface cracks appearing in upsetting operations such as heading when manufacturing screws and bolts.

It is of interest to be able to numerically predict whether cracks will occur before manufacturing an entire tool system for producing a component. In literature, several different approaches have been suggested for the prediction of cracks. In this paper, only uncoupled ductile damage criteria are considered.

Freudenthal [1] suggested a damage criterion based on the plastic work per volume:

$$D_{Freudenthal} = \int \bar{\sigma} d\bar{\varepsilon} \quad (1)$$

where $D_{Freudenthal}$ is the accumulated damage, $\bar{\sigma}$ is the effective stress and $d\bar{\varepsilon}$ the effective plastic strain increment. The main critique point to the Freudenthal criterion is that there is no distinction regarding whether the applied stresses are compressive or

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tensile. In fact, as it was originally demonstrated by Vujovic and Shabaik [2], the effective plastic strain at fracture is reduced with increasing hydrostatic tension.

A criterion based solely on the hydrostatic stress σ_m was proposed by Ayada et al. [3]:

$$D_{Ayada} = \int \frac{\sigma_m}{\bar{\sigma}} d\bar{\varepsilon} \tag{2}$$

Although eq. (2) considers the different crack initiation behaviour in compression and tension, it does not take into account shear stresses, which, according to Atkins and Mai [4], can also give rise to fracture.

Cockcroft and Latham [5] suggested a damage criterion based on the largest principal stress σ_1. A normalized version was introduced by Oh et al. [6]:

$$D_{Cockcroft-Latham} = \int \frac{\sigma_1}{\bar{\sigma}} d\bar{\varepsilon} \tag{3}$$

It is noticed that eq. (3) takes into account both stress triaxiality and shear stresses since both contribute to the largest, principal stress. It may therefore be seen as a hybrid criterion.

Recently, a shear stress criterion taking into account the influence of hydrostatic tension on shear cracking was proposed by Christiansen et al. [7]:

$$D_{Shear} = \int \frac{\tau}{\bar{\sigma}} d\gamma + \int \frac{3}{2}\frac{\sigma_m}{\bar{\sigma}} d\gamma \tag{4}$$

where τ is the shear stress and $d\gamma$ is the shear strain increment.

Since two different types of fracture, hydrostatic and shear were identified in Martins et al. [8], it is the aim and scope of this paper to compare the performance of a pure hydrostatic damage criterion (eq. (2)), a shear based criterion (eq. (4)) with the hybrid criterion (eq. (3)).

2. Experiments

2.1. Experiments and equipment

A set of bulk metal forming tests are performed in order to assess the performance of the aforementioned three ductile damage criteria (eqs. (2)-(4)). It consists of various workpiece geometries loaded to fracture. The experiments are performed on a 600kN hydraulic Mohr&Federhaff press. Corresponding load-stroke curves are recorded using a 500kN HBM C18 force transducer and a HBM WA 50mm length transducer. The experiments are performed on polished dies cleaned with gasoline.

Four different workpiece geometries are utilized: Flange, taper, shear and cylindrical, see Fig. 1. The flange, taper and shear specimens are loaded axially on the end surface with a plane overhanging tool. The cylindrical specimen is sideways compressed on the cylindrical surface with a plane tool. The flange, taper and cylindrical specimens are all loaded in increments, until visible surface cracks are observed, whereas the shear specimens are loaded in one operation until sudden fracture.

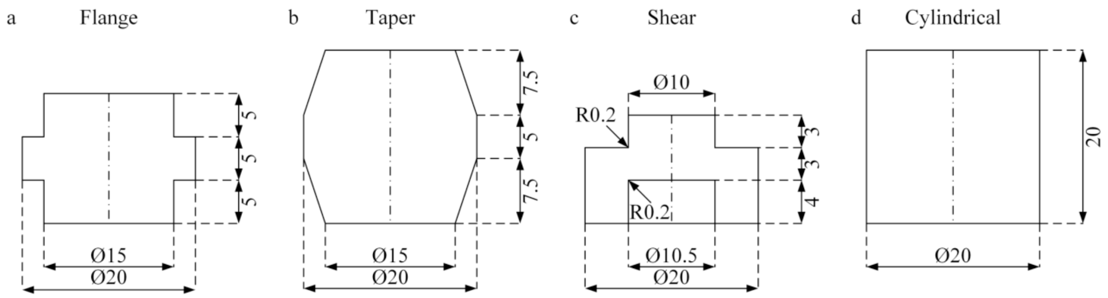

Fig. 1. Workpiece geometries utilized for formability determination; (a) Flange; (b) Taper; (c) Shear; (d) Cylindrical.

2.2. Workpiece materials and frictional conditions

The experiments are carried out with two different aluminium alloys; Al6351-T6 and Al2007-T6, both supplied as rods with initial diameters of Ø22mm and Ø20mm respectively and utilized in the “as-received” condition.

Stress-strain curves (Fig. 2a) are obtained by uniaxial upsetting of cylinders with initial dimensions (height x diameter) of 25x20mm and 20x20mm respectively. Thin teflon sheets are inserted in between dies and cylinders to minimize friction during the upsetting.

Friction between workpiece and dies in the formability tests are determined by ring tests. Rings of Al6351-T6 with initial outer and inner diameters of Ø18mm and Ø9mm and initial height of 6mm are compressed between two dies to various height reductions. The friction model proposed by Wanheim and Bay [9], $\tau = f\alpha k$, is assumed where τ is the frictional shear stress, $0 \le f \le 1$ is the friction factor, $0 \le \alpha \le 1$ is the relative contact area and k is the shear flow stress. A friction factor $f = 0.6$ is determined from the ring test, see Fig. 2b.

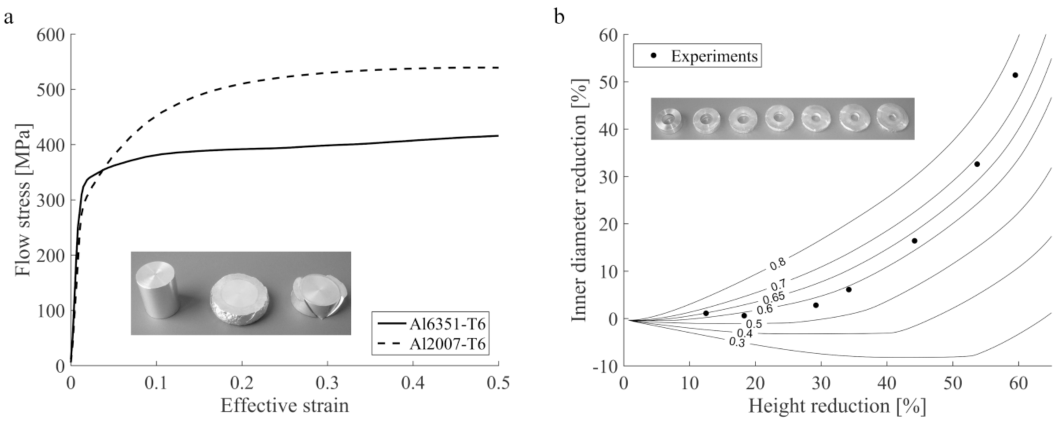

Fig. 2. (a) Stress-strain curves from upsetting test; (b) ring test with calibration curves for various f-values ($\tau = f\alpha k$).

Al6351-T6 is utilized for the flange, taper and shear experiments. Due to difficulties in locating the exact onset of cracking in the cylindrical compression test experiment, Al2007-T6 were used for these experiments, since it resulted in instantaneous cracking all through the cylinder. Examples of fractured specimens can be seen in Fig. 3b-e.

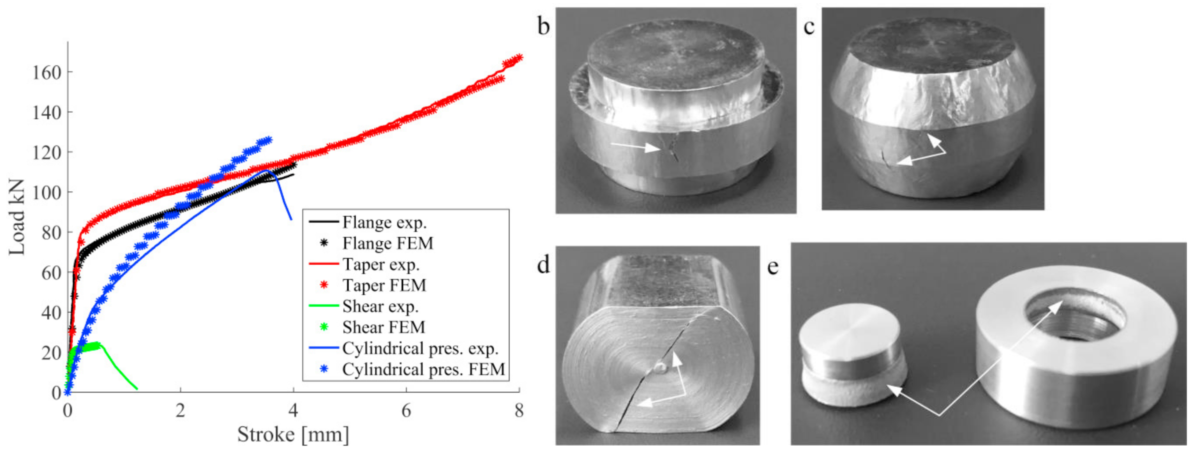

Fig. 3. (a) Comparison of experimental and FEM predicted load stroke curves; fractured specimens after compression; (b) flange; (c) taper; (d) cylindrical compression; (e) shear. The white arrows indicate cracks.

3. Results and discussion

3.1. FEM analysis

The in-house FE computer program I-FORM (for details regarding the program see Nielsen et al. [10]) was utilized to obtain the ring test calibration curves and to model the bulk formability tests. The stress-strain behaviour of the two aluminium alloys were based on tabulated data from the upsetting tests and the friction factor was taken from the ring test. Due to the slow movement of the hydraulic press during the experiments, quasi-static loading is assumed. Symmetry lines are utilized when possible. Quadrilateral elements with linear interpolation functions are utilized for meshing. The dies are modelled with rigid-contact elements. A comparison between experimental and FE predicted load-stroke curves can be seen in Fig. 3a. Except for the cylindrical compression test, good agreement between experimental and FEM-predicted loads are obtained.

Ductile damage according to eqs. (2)-(4) is computed for each case, however not necessarily presented in the paper. Damage accumulation in a load increment is set only to occur if the damage increment is positive, as suggested in Christiansen et al. [11].

3.1.1. Flange

The flange specimen was meshed with 1705 elements and most elements were located in the flange for better resolution.

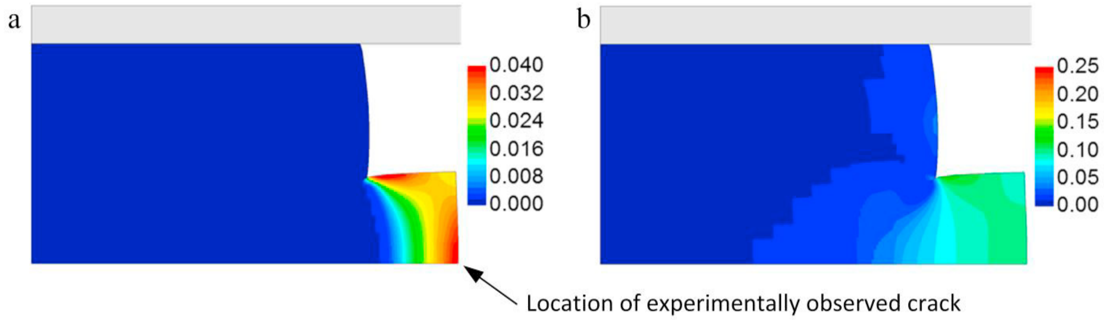

Fig. 4. Damage at fracture in the flange specimen for (a) Ayada and; (b) normalized Cockcroft and Latham ductile damage criterion.

It can be seen from Fig. 4 that both the Ayada and normalized Cockcroft and Latham criteria predict the location of fracture to be in the flange. However, the Ayada criterion predicts the crack to be at the surface either at the middle of the flange outer edge or in the corner region between the flange and cylindrical part. In the experiment, cracks were found to first form at the outer edge of the flange (Fig. 3b). However, in Silva et al. [12], hydrostatic tension was also found to initiate cracks in the flange corner, so the prediction by the Ayada criterion is physically meaningful. The normalized Cockcroft and Latham criterion gives a less distinctive prediction of the onset of cracks.

3.1.2. Taper

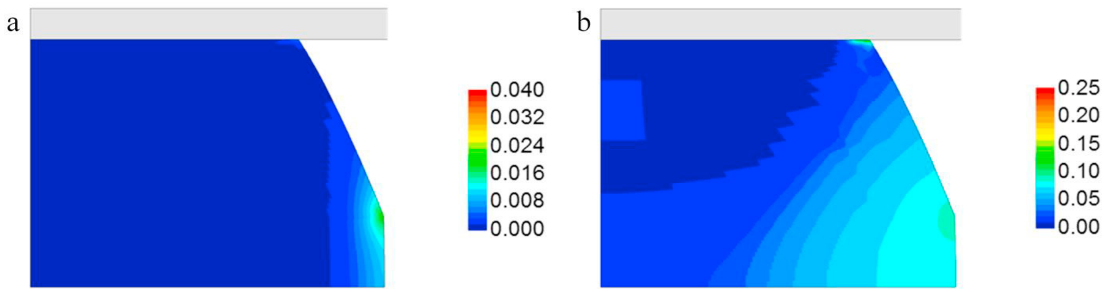

Fig. 5. Damage at fracture in taper specimen for (a) Ayada and; (b) Cockcroft and Latham ductile damage criterion.

The taper specimen was meshed with 2028 elements with more elements located in the middle region at the surface.

Fig. 5 shows a very local damage location when adopting the Ayada criterion. This is in agreement with experiments. The normalized Cockcroft and Latham criterion gives a more spread damage prediction but still predicts maximum damage at the location where cracks were observed experimentally (Fig. 3c).

3.1.3. Cylindrical

The cylindrical specimen was meshed with 4800 elements.

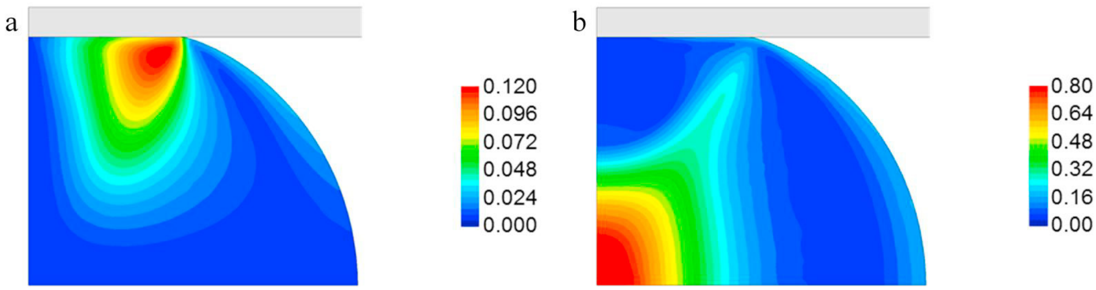

Fig. 6. Damage at fracture in flange component for (a) shear and; (b) normalized Cockcroft and Latham ductile damage criterion.

For the cylindrical compression seen in Fig. 6, both the shear and the normalized Cockcroft and Latham criteria give reasonable prediction of the location of damage. The normalized Cockcroft and Latham criterion seems somewhat better in capturing the shear under an inclined angle as observed in the experiment, see Fig. 3d. It is interesting to notice the difference in fracture initiation. The shear criterion predicts initiation in the corner at the interface between the component and the die, whereas the normalized Cockcroft and Latham criterion predicts crack initiation at the center.

3.1.4. Shear

The shear specimen was meshed with 4632 elements with most elements located in the shear zone.

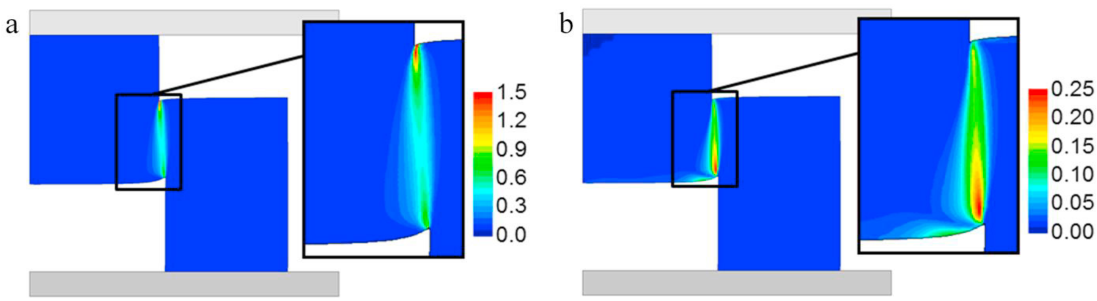

Fig. 7. Damage at fracture in flange component for (a) shear and; (b) normalized Cockcroft and Latham ductile damage criterion.

For the pure shear component seen in Fig. 7, both the shear and the normalized Cockcroft and Latham criteria predict correctly the location of damage (Fig. 3e), but disagree regarding the crack onset location.

3.2. Discussion

Three different ductile damage criteria have been applied for the prediction of cracks in various bulk metal forming operations.

The Ayada criterion was found to predict correctly the occurrence of cracks when they were formed due to hydrostatic tension. For the two components, flange and taper, a value of fracture of approximately 0.04 and 0.02 were obtained. Thus the order of magnitude is the same. This was also found in Silva et al. [12].

A newly developed shear based criterion predicted reasonably correct the location of cracks for the shear and cylindrical specimens. The damage values cannot be directly compared since two different aluminium alloys were utilized due to the difficulty in obtaining a well-defined onset of cracks for the cylindrical compression.

The normalized Cockcroft and Latham criterion predicts the overall location of cracks for the flange and taper components. The location is, however, not as precisely predicted as for the Ayada criterion for those two components. For the pure shear and the cylindrical compression specimens, both the shear and normalized Cockcroft and Latham criteria predict correctly the location of cracks. However, they do not agree on the location of the crack initiation. For the flange, taper and shear specimens, the damage value at fracture is ranging from 0.1 to 0.25 for the normalized Cockcroft and Latham criterion, hence the order of magnitude is the same for the various experiments.

4. Conclusion

Based on the experiments and the numerical simulations it can be concluded that the Ayada criterion accurately predicts the occurrence of cracks due to hydrostatic tension. The shear criterion predicts the location of cracks due to shear stresses. The normalized Cockcroft and Latham criterion also predicts the overall location of cracks caused by hydrostatic tension, however less accurate than the Ayada criterion. It also predicts the occurrence of shear cracks reasonably correct for the geometries investigated.

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References

[1] A.M. Freudenthal, The inelastic behaviour of engineering materials and structures, first ed., John Wiley & Sons, 1950.
[2] V. Vujovic, A.H. Shabaik, A new workability criterion for ductile metals, J. Eng. Mater. Tech. 108 (1986) 245-249.
[3] M. Ayada, T. Higashino, K. Mori, Central bursting in extrusion of inhomogeneous materials, Proc. 2nd ICTP, Stuttgart, 1987, Vol. 1, pp. 553-558.
[4] A.G. Atkins, Y. W. Mai, Elastic and plastic fracture: metals, polymers, ceramics, composites, biological materials, first ed., Ellis Horwood, 1985.
[5] M.C. Cockcroft, D.J. Latham, Ductility and workability of metals, J. I. Met. 96 (1968) 33-39.
[6] S.I. Oh, C.C. Chen, S. Kobayashi, Ductile fracture in axisymmetric extrusion and drawing - Part 2 Workability in extrusion and drawing, J. Eng. Ind. 101 (1979) 36-44.
[7] P. Christiansen, C.V. Nielsen, N. Bay, P.A.F. Martins, Internal shear cracking in bulk metal forming, accepted for publication in Proc. IME J. Mater. Des. Appl. (2016).
[8] P.A.F. Martins, N. Bay, A.E. Tekkaya, A.G. Atkins, Characterization of fracture loci in metal forming, Int. J. Mech. Sci., 83 (2014) 112-123.
[9] T. Wanheim, N. Bay, A model for friction in metal forming processes, CIRP Annals 27 (1978) 189-194.
[10] C.V. Nielsen, W. Zhang, L.M. Alves, N. Bay, P.A.F. Martins, Modeling of Thermo-Electro-Mechanical Manufacturing Processes, first ed., Springer, 2013.
[11] P. Christiansen, J.H. Hattel, N. Bay, P.A.F. Martins, Modelling of damage during hot forging of ingots, STEELSIM 2013.
[12] C.M.A. Silva, L.M. Alves, C.V. Nielsen, A.G. Atkins, P.A.F. Martins, Failure by fracture in bulk metal forming, J. Mater. Process. Technol. 215 (2015) 287-298.